Introduction to Composite Materials
(Laminated Composite Materials)

Mechanical Engineering

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2007 Titus Racer X Exogrid

The Full Page Ad for 2007 Titus Racer X Exogrid

My wish
What are you going to learn?

- What are composite materials?
- How are they manufactured?
- What advantages and drawbacks do composites have over metals?
- Develop mathematical models to understand the mechanical response of composites to mechanical and hygrothermal loads?
- Use the above mathematical models to optimally design structures made of composites.

What is a composite?

- A composite is a structural material which consists of combining two or more constituents
- Examples:
  - Flesh in your leg reinforced with bones
  - Concrete reinforced with steel
  - Epoxy reinforced with graphite fibers.

Shift in Paradigm About Materials

- “You are no longer to supply the people with straw for making bricks; let them go and gather their own straw” - Exodus 5:7.

“More important than any one new application is the new ‘materials’ concept itself ”
Peter F. Drucker
The Age of Discontinuity, 1969
What is this paradigm shift in materials?

- From substance to structures
- From artisan to science
- From workshop to mathematical modeling
- From what nature provides to what man can accomplish

From constituents to application

Chapter 1
Introduction to Composite Materials

Short Videos on Composite Materials

- Some videos of composite materials
- NASA uses composite materials in shuttle
- Composites improve efficiency
- Cloth composites
Chapter 1: Objectives

- What is a composite?
- What are the advantages and drawbacks of composites over monolithic materials?
- What factors influence mechanical properties of a composite

Chapter Objectives (continued)

- How do we classify composites?
- What are the common types of fibers and matrices?
- How are composite materials manufactured?
- What are the mechanical properties of composite materials?

Chapter Objectives (continued)

- Give applications of composite materials.
- How are composites recycled?
- What terminology is used for studying mechanics of composites?

What is an advanced composite?

- Advanced composites are composite materials which were traditionally used in aerospace industries

Examples include graphite/epoxy, Kevlar/epoxy and Boron/aluminum
Examples of Natural Composites

- Wood
  - Cellulose Fibers
  - Lignin Matrix
- Bones
  - Collagen Fibers
  - Mineral Matrix

Why composites over metals?

- High Strength and High Stiffness
- Tailored Design
- Fatigue Life
- Dimensional Stability
- Corrosion Resistance

Why Composites over Metals?

- How is the mechanical advantage of composite measured?

\[
\text{Specific modulus} = \frac{E}{\rho},
\]

\[
\text{Specific strength} = \frac{\sigma_{ult}}{\rho}
\]

where
- \( E \) = Young’s Modulus
- \( \rho \) = Density
- \( \sigma_{ult} \) = Ultimate Strength

Specific Strength vs. Year
Table 1.1. Specific modulus and strength of typical fibers, composites and bulk metals

<table>
<thead>
<tr>
<th>Material</th>
<th>Specific Gravity</th>
<th>Young's Modulus</th>
<th>Ultimate Strength</th>
<th>Specific Modulus</th>
<th>Specific Strength</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>[GPa]</td>
<td>[GPa] m/m/kg</td>
<td>[GPa] m/m/kg</td>
<td>[GPa] m/m/kg</td>
<td>[GPa] m/m/kg</td>
</tr>
<tr>
<td>Steel</td>
<td>7.8</td>
<td>207</td>
<td>648</td>
<td>0.026</td>
<td>0.083</td>
</tr>
<tr>
<td>Cross-Ply Graphite/Epoxy</td>
<td>0.84</td>
<td>278</td>
<td>848</td>
<td>0.026</td>
<td>0.083</td>
</tr>
<tr>
<td>Quasi-Isootropic Graphite/Epoxy</td>
<td>0.84</td>
<td>278</td>
<td>848</td>
<td>0.026</td>
<td>0.083</td>
</tr>
</tbody>
</table>

Comparative Thermal Expansion Coefficients (μin/in/°F)

<table>
<thead>
<tr>
<th>Material</th>
<th>Direction-x</th>
<th>Direction-y</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steel</td>
<td>6.5</td>
<td>6.5</td>
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<tr>
<td>Aluminum</td>
<td>12.8</td>
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</tr>
<tr>
<td>Graphite</td>
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<td>1.1</td>
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<tr>
<td>Unidirectional Graphite/Epoxy</td>
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<tr>
<td>Cross-Ply Graphite/Epoxy</td>
<td>0.84</td>
<td>0.84</td>
</tr>
<tr>
<td>Quasi-Isootropic Graphite/Epoxy</td>
<td>0.84</td>
<td>0.84</td>
</tr>
</tbody>
</table>

Other Mechanical Parameters

- Are specific modulus and specific strength the only mechanical parameters used for measuring the relative advantage of composites over metals? NO!

Critical load, \( P_\sigma = \frac{\pi^2 E I}{L^2} \)

Second moment of area, \( I = \frac{d^4}{12} \)

Mass, \( M = \rho \frac{\pi d^4 L}{4} \)

\[
M = 2L \left( P \frac{d}{3E} \right) = 2L \left( \frac{P}{\pi} \right)^{\frac{3}{2}} \frac{\rho}{E}
\]
**Tailored Design**

- Engineered to meet specific demands as choices of making the material are many more as compared to metals.
- Examples of choices
  - fiber volume fraction
  - layer orientation
  - type of layer
  - layer stacking sequence

**Fatigue Life**

- Fatigue life is higher than metals such as aluminum.
- Important consideration in applications such as
  - aircrafts
  - bridges
  - structures exposed to wind

**Dimensional Stability**

- Temperature changes can result
  - in overheating of components (example engines)
  - thermal fatigue due to cyclic temperature changes (space structures)
  - render structures inoperable (space antennas)

**Corrosion Resistance**

- Polymers and ceramics matrix are corrosion resistant
- Examples include
  - underground storage tanks
  - doors
  - window frames
  - structural members of offshore drilling platforms
What is most limiting factor in the use of composites in structures?

Lack of engineers with the knowledge and experience to design with these materials!!!!

Cost Considerations

- Composites may be more expensive per pound than conventional materials. Then why do we use composite materials?

Factors in Cost Estimate

- For Composite Materials
  - Fewer pounds are required
  - Fabrication cost may be lower
  - Transportation costs are generally lower
  - Less maintenance than conventional materials is required

Fiber Factors

- What fiber factors contribute to the mechanical performance of a composite?
  - Length
  - Orientation
  - Shape
  - Material
Fiber Factor - Length

- Long Fibers
  - Easy to orient
  - Easy to process
  - Higher impact resistance
  - Dimensional stability
- Short Fibers
  - Low Cost
  - Fast cycle time

Fiber Factor - Orientation

- One direction orientation
  - High stiffness and strength in that direction
  - Low stiffness and strength in other directions
- Multi-direction orientation
  - Less stiffness but more direction independent

Fiber Factor - Shape

- Most common shape is circular
- Hexagon and square shapes give high packing factors

Fiber Factor - Material

- Graphite andaramids have high strength and stiffness
- Glass has low stiffness but cost less
Matrix Factors

- What are the matrix factors which contribute to the mechanical performance of composites?
  - Binds fibers together
  - Protects fibers from environment
  - Shielding from damage due to handling
  - Distributing the load to fibers.

Factors Other Than Fiber and Matrix

- Fiber-matrix interface
  - Chemical bonding
  - Mechanical bonding

Fiber Types

- Glass Fiber (first synthetic fiber)
- Boron (first advanced fiber)
- Carbon
- Silicon Carbide

Types of Matrices

- Polymers
- Metals
- Ceramics
Polymer Matrix

- Thermosets
  - polyester
  - epoxy
  - polymide
- Thermoplastics
  - polypropylene
  - polyvinyl chloride
  - nylon

Metal Matrix

- Aluminum
- Titanium
- Copper

Ceramic Matrix

- Carbon
- Silicon Carbide
- Calcium AluminoSilicate
- Lithium AluminoSilicate

Why do fibers have thin diameter?

- Less flaws
- More toughness and ductility
- Higher flexibility

Thin Fiber

Thick Fiber
Less Flaws

- Fiber-matrix interface area is inversely proportional to the diameter of the fibers
- Higher surface area of fiber-matrix interface results in higher ductility and toughness, and better transfer of loads.

More Flexibility

- Flexibility is proportional to inverse of
  - Young's modulus
  - Fourth power of diameter
- Thinner fibers hence have a higher flexibility and are easy to handle in manufacturing.

More Toughness and Ductility
Fibrous Composites

- Generally there are two phases
  - Fiber as a reinforcement
  - Matrix as a binder

Historical Perspective

- 4000 B.C.: Fibrous composites were used in Egypt in making laminated writing materials
- 1300 BC: Reference to Book of Exodus
- 1700 AD: French Scientist, Reumer talked about potential of glass fibers

Historical Perspectives (continued)

- 1939: Glass fiber manufactured commercially for high temperature electrical applications
- 1950s: Boron and carbon fibers were produced to make ropes.
- 1960s: Matrix added to make polymeric matrix composites

Historical Perspectives (continued)

- 1970s: Cold war forces development of metal matrix composites for military aircrafts and missile guidance systems
- 1990s: High temperature ceramic matrix composites are being aggressively researched for use in next generation aircraft engines and power plant turbines
Shipments of Composites

World Market of Composites

Advantages of Composites
- Specific Strength and Stiffness
- Tailored Design
- Fatigue Life
- Dimensional Stability
- Corrosion Resistance
- Cost-Effective Fabrication

Drawbacks of Composites
- High cost of fabrication of composites
- Complex mechanical characterization
- Complicated repair of composite structures
- High combination of all required properties may not be available
Composites vs. Metals

- Comparison based on six primary material selection parameters

Are Composites Important?

- Considered as one of the ten outstanding achievements of 1964-1980